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ACCURATE OSCILLATOR STRENGTHS FOR ULTRAVIOLET LINES OF Ar I: IMPLICATIONS FOR INTERSTELLAR MATERIAL

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ABSTRACT

Analysis of absorption from interstellar Ar I in lightly reddened lines of sight provides information on the warm and hot components of the interstellar medium near the Sun. The details of the analysis are limited by the quality of the atomic data. Accurate oscillator strengths for the Ar I lines at 1048 and 1067 Å and the astrophysical implications are presented. From lifetimes measured with beam-foil spectroscopy, an *f*-value for λ1048 of 0.257 ± 0.013 ($1\ \sigma$) is obtained. Through the use of a semiempirical formalism for treating singlet-triplet mixing, an oscillator strength of 0.064 ± 0.003 ($1\ \sigma$) is derived for λ1067. Because of the accuracy of the results, the conclusions of York and colleagues from spectra taken with the *Copernicus* satellite are strengthened. In particular, for interstellar gas in the solar neighborhood, argon has a solar abundance, and the warm, neutral material is not pervasive.

Subject headings: atomic data — atomic processes — ISM: abundances — ultraviolet: interstellar

1. INTRODUCTION

The observed structure of interstellar material within the Galactic disk has been a matter of debate. In their model of a three-component interstellar medium, McKee & Ostriker (1977) suggested that most of the volume was occupied by hot gas produced by expanding supernova remnants. Evidence for this hot gas includes ultraviolet observations of O VI absorption toward O and B stars (e.g., Jenkins & Meloy 1974; York 1974). From radio observations, Heiles (1980), however, inferred that most of the material in the disk is warm and neutral. Heiles concluded that this intercloud material was H I gas which is not strongly absorbing. Optical studies of lightly reddened lines of sight, such as those toward λ Sco and α Vir, are especially suitable for examining the relative contributions of warm and hot gas in local interstellar matter (York & Kinahan 1979; York 1983), as well as the physical conditions within the gas. The structure from local and global perspectives, however, need not be the same.

When the width of an interstellar absorption line characterizes a gas temperature, this Doppler width is expected to vary inversely with the square root of atomic mass. Such a trend was observed in local interstellar gas along several lines of sight. For the line of sight to λ Sco, York (1983) found that $b(\text{H I}) > b(\text{D I}) > b(\text{O I}) > b(\text{Ar I})$ for the main component containing warm ($T \sim 10^4$ K), neutral gas. York & Kinahan (1979) found a similar trend for the gas in the direction of α Vir. These trends then formed the basis for an estimate of the relative contributions of warm and hot gas in the solar neighborhood.

Two complications arise when interpreting the observational results. One is that physically distinct regions may not be distinguishable if their separation in velocity is small. The other involves uncertainties associated with oscillator strengths. Atomic absorption lines are usually analyzed by varying the central wavelength, the column density, and the *b*-value for each component until an optimal fit to the profile is achieved (e.g., York 1983). Uncertainties in oscillator strength translate into uncertainties in column density and *b*-value. As noted by Morton (1991), the results from a variety of experimental techniques for Ar I $\lambda\lambda$ 1048, 1067 span an uncomfortably large range. This paper presents the most accurately determined mean lives for the Ar I lines at 1048 and 1067 Å, the corresponding oscillator strengths, and the consequences for the interpretation of previous observational results for interstellar Ar I. The present work strengthens the conclusions obtained previously for local interstellar material: The argon abundance is essentially solar, and the warm, neutral gas occupies a small fraction of the sight line between the Sun and star.

The experimental and semiempirical techniques used to determine the mean lives are described in the next section. This is followed by a presentation of the atomic data for Ar I. Our *f*-value for λ1048 represents the most precise result available; the *f*-value for λ1067, which is derived from our measurements on λ1048, is of comparable precision and is consistent with other accurate experimental determinations. In § 4, these data are used to interpret interstellar absorption lines seen toward lightly reddened lines of sight. In particular, the weaker transition at 1067 Å is used to derive the argon column density, while the ratio of *f*-values allows a determination of the Doppler width. Our results are summarized in the final section.

2. TECHNIQUES

2.1. *Experimental*

The Toledo Heavy Ion Accelerator produces an isotopically pure beam of almost any desired element at an energy up to 330 keV (Haar 1989). The ions are produced in a universal ion source, have their momentum analyzed at 10–30 keV by a Danfysik isotope separator to ensure high mass resolution, and then are accelerated to 100–330 keV. The beam is transported into an interaction chamber containing a precisely translatable mount which carries a turret with a supply of 2 μg cm^{-2} self-supporting carbon foils. The passage of the ions through a foil produces the requisite neutralization and excitation. Light is analyzed with an Acton 1 m VUV monochromator equipped with two externally selectable gratings, two separate exit slits, and two photodetectors. Here, detection is by single photon-counting techniques with a Galileo channeltron electron multiplier. By moving the foil relative to the monochromator entrance slit, time-resolved decay curves are acquired.

Decay curves were obtained for the transition $3p^6$–$3p^5 4s[3/2]_1$ of neutral argon at 1048.2 Å. Beams of Ar^+ with energies of 170 keV and 220 keV were produced in the heavy ion accelerator. Typical beam currents through a 6 mm diameter collimator were 100–200 nA. Normalization to the intensity of light collected by an optical fiber bundle located a fixed distance from the foil served to correct for variations in beam current and changes in foil characteristics. Beam currents and dwell times were chosen so that the acquisition time for a typical decay curve would be about 70% of the expected time before foil breakage (Hellborg et al. 1991). Decay curves from a number of different foils were superposed and analyzed. In general, 1500–2500 counts at the peak of each composite curve were realized.

The decay curve for this transition is expected to be heavily affected by cascade repopulation from the many possible $4s$–$4p$ and $4s$–$5p$ transitions. The ANDC analysis technique (Curtis, Berry, & Bromander 1970)—useful when the repopulation is dominated by a small number of observable cascades—is not easily applied here. However, the $4s$–$4p$ and $4s$–$5p$ transition arrays have been carefully investigated by Wiese et al. (1989), and the mean life of even the shortest lived of these is more than an order of magnitude longer than that expected for the primary decay (Wiese, Smith, & Miles 1969). Thus, in this case, a reliable value for the primary mean life can be extracted from a simple multiexponential fit. On the other hand, parameterization of the decay curve as the sum of a small number of exponentials is an approximation and this proved to be the ultimate limitation on the accuracy attainable. Various methods of parameterizing and representing the long-time behavior of the decay curves were investigated in order to ascertain the sensitivity of the extracted value of the primary mean life to these assumptions. A precision of about 4% was established.

A second, somewhat smaller, source of uncertainty in the reported mean life is due to lack of exact knowledge of the effective postfoil beam velocity. The prefoil velocity can be measured to better than 0.2% using a cylindrical electrostatic analyzer calibrated by a variant of the technique of Schectman et al. (1988); in most cases, the velocity was obtained from a somewhat less accurate secondary calibration involving the accelerator power supply voltmeters (Fakhruddin 1988). A series of helium quantum beat measurements confirmed the calibration. This uncertainty never exceeded 2%.

At the ion velocities encountered in this experiment, nuclear and electronic energy losses contribute comparably to the slowing of the beam as it traverses the foil. This precludes use of the electrostatic analyzer for determining the effective postfoil velocity because the analyzer does not detect ions deflected by nuclear scattering through larger angles, whose radiation nevertheless is viewed by the monochromator (Anderson, Madsen, & Sorenson 1972). Calculated values of the energy loss (Lindhard, Nielsen, & Scharff 1968) are therefore used to determine the final velocity; it is assumed that this contributes an uncertainty in the postfoil beam energy equal to half of the nonforward nuclear scattering (Hvelplund et al. 1970; Garnir-Monjoie & Garnir 1980). In no case does the velocity uncertainty due to this ambiguity exceed 1%. Uncertainty in the actual value of the foil thickness may also contribute an uncertainty in the mean life of about 1%. Lifetimes were measured at both 170 and 220 keV—where the energy losses in the foil differ—and agree well within the quoted uncertainty.

Another possible systematic effect which can distort the time scale is foil thickening. Estimates based upon the data of Dumont et al. (1976) suggest that errors due to this effect should, in the present experiment, be smaller than those due to nuclear scattering. As a check, composite decay curves were measured with the foil moving both up-beam and down-beam and were analyzed separately. All trials gave consistent mean lives.

Finally, we mention the fact that at low energy, beam divergence due to multiple Coulomb scattering may cause ions to scatter out of the monochromator viewing region and lead to an anomalously short measured mean life. Calculations based upon the formalism of Meyer (1971) were used to set a lower limit on the energies for which decay curves were measured; the agreement between mean lives extracted at different energies described above demonstrates that multiple scattering was not significantly affecting these measurements. A data acquisition routine, ACCEL, written by Roger Haar (1989) not only controlled the experiment and acquired and displayed the results, but also provided the user with calculated values for the estimated foil-breakage time, the electronic energy loss, the forward and nonforward nuclear energy loss, and the rms multiple scattering angle in order to simplify the choice of optimum experimental parameters.

2.2. *Semiempirical Analysis*

The decay of the Ar I transition $3p^6$–$3p^5 4s[1/2]_1$ at 1066.7 Å is less amenable to direct measurement because the mean life of the upper level is expected to be nearly 5 times longer than that of the line at 1048 Å (Wiese et al. 1969). In such cases, equally good multiexponential fits can often be obtained using significantly different values of the fitting constants (Lanczos 1956). For this reason we were unable to make a direct lifetime determination with sufficient accuracy to resolve the discrepancies between previous measurements. However, we observe that the ratio of the mean lives of these two transitions can be obtained semiempirically with good precision, and we recommend combining this ratio with the accurate value of the mean life of $[3/2]_1$ reported here to specify the value of the mean life of $[1/2]_1$. Curtis (1989, 1991) demonstrated that when an s and a p electron or hole are coupled, the experimental energies of the resulting four P levels can be used to determine the degree of mixing of the $^3P_1$ and $^1P_1$ levels, and that this often makes it possible to predict accurate transition probabilities and g-factors. Here, the configuration $3p^5 4s$ gives rise to the four levels:

$$[1/2]_0 = {}^3P_0\ ,$$
$$[3/2]_2 = {}^3P_2\ ,$$
$$[1/2]_1 = -\sin(\theta)\,{}^1P_1 + \cos(\theta)\,{}^3P_1\ , \quad \text{and}$$
$$[3/2]_1 = \cos(\theta)\,{}^1P_1 + \sin(\theta)\,{}^3P_1\ ,$$

where the mixing of the two $J = 1$ levels is specified by θ. For a pure JK state, $\tan(\theta)$ would be 0.707. The actual mixing parameter can be obtained by a fit to the spectroscopically determined term values of the four levels of the configuration

(Minnhagen 1973), with Slater integrals, the spin-orbit integral, and the mixing angle as free parameters. The most likely source of a breakdown of this approach would be additional mixing with levels of other configurations; however, the nearest $J = 1$ odd parity levels are over 2 eV away and a simple *ab initio* calculation carried out using the Cowan program (Cowan 1981) to include the $3p^5 5s$ and $3p^5 3d$ configurations shows less than a 1% admixture of any level arising from these closest configurations. The mixing angle which results from the four experimental term values is $\tan(\theta) = 0.504$. The ratio of the line strengths for the two transitions then follows immediately as $\tan^2(\theta)$.

3. RESULTS

Analysis of the measured decay curves for λ1048 yields a mean life of 1.92 ± 0.08 ns, where the quoted uncertainty is 1 σ. Use of the mixing-angle formalism with this experimental value gives a mean life of 7.96 ± 0.33 ns for λ1067. Since these decay channels are the only important ones, the mean lives can be converted directly to oscillator strengths, as

$$f = \frac{g_u}{g_l}\left(\frac{\lambda}{2582.7}\right)^2 \tau^{-1} , \tag{1}$$

where λ is in Å and τ is in nanoseconds. The resulting oscillator strengths are $f(1048) = 0.257$ and $f(1067) = 0.064$; both are accurate to 5%.

Our values compare favorably with the respective values of 0.244 and 0.067 recently suggested by Morton (1991), who took an average of mean life and oscillator-strength measurements obtained by a variety of experimental techniques. The techniques included line-broadening measurements (Lewis 1967; Copley & Camm 1974; Vallee, Ranson, & Chapelle 1977), pulsed electron beams (Lawrence 1968), beam-foil spectroscopy (Irwin, Livingston, & Kernahan 1973), and self-absorption measurements (de Jongh & van Eck 1971). When necessary, Morton converted mean lives into oscillator strengths as described earlier. A problem noted was the large range of values about the mean. Although not included in Morton's compilation, Westerveld, Mulder, & van Eck (1979) refined the self-absorption technique and derived an oscillator strength for λ1048 about 10% larger than that of de Jongh & van Eck, and Li et al. (1988) obtained *f*-values by electron–energy-loss spectroscopy. Moreover, Chornay, King, & Buckman (1984) used a coincidence technique involving electron excitation with photon decay and found a lifetime for λ1067 of 7.9 ± 0.6 ns; this technique is not susceptible to the cascading encountered by us. As seen from Table 1, our mean life for λ1048 is consistent with those from the other experiments, but of higher accuracy, and our estimate of the mean life of λ1067 is in excellent agreement with the measured value of Chornay et al. Good agreement is also found with the theoretical results of Lee (1974), who obtained *f*-values of 0.278 ± 0.028 and 0.070 ± 0.007, respectively. Inclusion of all laboratory results yields weighted mean oscillator strengths of $f(1048) = 0.247 \pm 0.007$ and $f(1067) = 0.063 \pm 0.002$.

4. ASTROPHYSICAL IMPLICATIONS

Our precise *f*-values can be used to refine the interpretation of Ar I absorption in the interstellar medium. Because the resonance lines at λλ 1048, 1067 are quite strong, analyses that are performed in order to extract information about physical conditions should be restricted to sight lines with small amounts of neutral material. The data from Ar I absorption are most reliable when the optical depth at line center for λ1048 is less than ∼15. This optical depth is attained for equivalent widths (W_λ) of 25 mÅ when $b = 2$ km s^{-1}; the corresponding column density is about 7×10^{13} cm^{-2}. For larger W_λ, both column density and Doppler width cannot be determined with confidence. The data for the line of sight toward λ Sco fulfill this requirement and are of sufficiently high quality for an investigation of local interstellar material.

The *Copernicus* data for neutral argon toward λ Sco (York 1983) were originally analyzed with *f*-values quoted by Morton & Smith (1973), $f(1048) = 0.230$ and $f(1067) = 0.0594$. These values are within 10% of the values found here. The important point is that the improved accuracy of our results removes any doubt remaining concerning the astronomical findings. First, the derived column density of argon from Ar I lines for the main component at −32 km s^{-1} indicates an abundance which is essentially solar, much like the abundances for nitrogen and oxygen. The column density was obtained from W_λ for the weaker line at 1067 Å; the equivalent width is small enough so that the determination is not dependent on *b*-value. As a result, the column density scales with *f*-value and is about 8% smaller than that given earlier by York (1983). However, the revised argon abundance is still consistent with the solar value because recent estimates for the abundance of Ar in the Sun

TABLE 1

EXPERIMENTAL RESULTS FOR THE ARGON I RESONANCE LINES[a]

REFERENCE	λ1048		λ1067		TECHNIQUE
	τ (ns)	f	τ (ns)	f	
Lewis 1967	1.77(13)[b]	0.278(20)	8.09(51)[b]	0.063(4)	Line-broadening
Copley & Camm 1974	1.74(15)[b]	0.283(24)	6.70(35)[b]	0.076(4)	Line-broadening
Vallee et al. 1977	2.35(34)[b]	0.210(30)	9.99(137)[b]	0.051(7)	Line-broadening
Lawrence 1968	2.15(20)	0.230(21)[c]	8.6(4)	0.059(3)[c]	Pulsed electron
Irwin et al. 1973	1.4(5)	0.35(13)[c]	6.2(20)	0.082(26)[c]	Beam-foil
de Jongh & van Eck 1971	2.2(2)[b]	0.22(2)	...	...	Self-absorption
Westerveld et al. 1979	2.06(17)[b]	0.240(20)	8.09(64)[b]	0.063(5)	Self-absorption
Chornay et al. 1984	...	...	7.9(6)	0.064(5)[c]	Coincidence
Li et al. 1988	2.22(25)[b]	0.222(25)	8.78(90)[b]	0.058(6)	Energy-loss
Present results	1.92(8)	0.257(13)[c]	7.96(33)[b]	0.064(3)[d]	Beam-foil

[a] Numbers in parentheses are the quoted 1 σ accuracies.

[b] Obtained from oscillator strength.

[c] Obtained from mean life.

[d] Based on mixing-angle formalism.

and nearby young stars are also slightly lower than previously thought (see Keenan et al. 1990). In another line of sight sampling local gas, that toward α Vir, the velocity of neutral and ionized gas was not resolved by the *Copernicus* satellite (York & Kinahan 1979), but again the argon abundance appears to be solar. Since sulfur is also expected to have an abundance that is nearly solar, the apparent overabundance for sulfur toward α Vir most likely arises from contaminating S II absorption associated with H II regions along the line of sight. Attributing the additional S II absorption to ionized gas could explain the puzzling results of Duley (1985) on sulfur depletion relative to argon depletion. It would then be possible that the sulfur depletion, D_S, goes to zero as D_{Ar} goes to zero and that little or no sulfur is incorporated in grains when $D_{Ar} \rightarrow 0$.

Once the column density for Ar I is set by the results for λ1067, the *b*-value can be estimated from W_λ for the line at 1048 Å. A column density of 2.4×10^{13} cm^{-2} for the main component toward λ Sco yields a *b*-value of 1.7 km s^{-1}; this is the value obtained by York (1983). Thus, a second conclusion is that the line width for the Ar I lines is indeed small, and that the trend of decreasing width with increasing atomic mass indicates thermal broadening. The temperature derived from the *b*-value is $\sim 10^4$ K; thus the gas at -32 km s^{-1} toward this star represents a warm, neutral component of the interstellar medium. With this temperature, the density derived from the relative populations of C II fine structure levels is $n > 1$ cm^{-3}. N II* absorption at this velocity is weak, at the level of detection (York 1983), indicating that the estimated density should not be significantly affected by ignoring this ionized gas. One then concludes that the gas is in a clump of size no larger than about 1 pc, which is much smaller than the ~ 100 pc distance to the star. Therefore, most of the volume between the Sun and λ Sco is *not* warm, neutral gas.

This result for material in the solar neighborhood contrasts with the global result from radio data, where Heiles (1980) found the warm gas to be pervasive in the disk as a whole. Since we observe that within the local hot superbubble, warm gas occupies only a small part of the volume, Heiles's result would then suggest that a much larger fraction of the material outside the bubble is comprised of warm gas. The radio data are best described as representing the disk as a whole, with the local superbubble as one of the bounded regions of hot gas distributed throughout the disk. The disagreement between the predictions of McKee & Ostriker (1977) and the observations of Heiles concerning the relative global ratio of the hot and warm components cannot be reconciled solely by local observations.

5. SUMMARY

In conclusion, an accurate laboratory-based *f*-value of 0.257 ± 0.013 (1 σ) for Ar I λ1048 was obtained. This *f*-value, in conjunction with the use of measured energy levels to establish the degree of mixing between the $^1P_1$ and $^3P_1$ levels, yielded an *f*-value of 0.064 ± 0.003 (1 σ) for λ1067. The data are most useful in analyzing Ar I observations toward lightly reddened directions; otherwise, saturation of these strong lines presents a problem. Our atomic data are more accurate than those used in previous studies of local interstellar matter, and as a result, strengthen the conclusions concerning the nature of the gas toward λ Sco and α Vir. In these lines of sight, argon is observed to have a solar abundance. Since the argon abundance is solar, the apparent overabundance of sulfur in the neutral gas toward α Vir may well be caused by contributions from S II absorption associated with H II regions along the line of sight. Finally, we observe that the warm, neutral gas occupies only a small part of the local superbubble.

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Note added in proof.—Subsequent to the acceptance of this manuscript, a measurement of *f*-values in Ar I, of similar accuracy to those of this work, was reported by Chan et al. (Phys. Rev., A46, 149 [1992]). Agreement between our results for *f*(1048) and *f*(1067) and their values is excellent.